Analysis of Woven Fabrics and Fiber Composite Material 
Aerospace Parts using Industrial CT Data

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Abstract
Modern lightweight structures such as fiber composites and woven fabrics play an important role in today's aerospace industry. These materials facilitate a significant weight reduction. For parts subject to high stress, which is typical in this industry, the draping of woven fabrics to suite the endurable forces is of utmost importance. Complex curved and bent geometries are very common and may lead to complex distortions and deformations of the woven fabrics and their layers. The possibility to use CT scan data to extract information of the fibers in woven fabrics creates an excellent data basis for more precise simulations of the mechanical properties of fiber composites and serves as reference for a simulation of the manufacturing process itself [1].

We previously developed and presented algorithms [2] to analyse the orientations of the fibers as well as the fiber volume fraction using CT scan data of fiber composites. In this paper we demonstrate how these algorithms may be applied to gather indispensible information about the actual fiber orientations in woven fabrics using examples from the aerospace industry. The designed layer structure of organic sheets often does not match reality, and the actual position of the layers has to be detected in the scan data, e.g., for comparison with simulation results. It is now possible to not only determine a single predominant orientation of the fibers, but instead multiple principal axes can be calculated within the woven fabric layers. Furthermore the positions of the individual fabric layers can be detected using the analysis results. It is possible to obtain meaningful results even if the scan resolution does not allow segmentation of the individual rovings because the analysis works directly on the gray values of the CT data. For comparison with simulation results, an integration mesh may be manually defined or imported from a simulation software and then automatically adjusted to the real layer structure of the actual scanned part. Also statistical information will be calculated and the results can be visualized in our software and exported to a simulation software together with the adjusted simulation mesh.

Keywords: industrial CT, aerospace, woven fabrics, orientation analysis, simulation

1. Introduction

Fiber enforced materials, especially woven fabrics, are used more and more often in today's aerospace industry to design lightweight products. The distribution and orientations of the fibers play an important role for the mechanical properties of those parts. Precise knowledge of the orientations is needed and facilitate accurate mechanical simulations. Using industrial CT-data it is now possible to analyze such parts without destroying them and to both compare the real internal structure with the simulated one and also to use the actual orientations for even more precise simulations.

2. Analysis of woven fabrics CT scan data

In the following we demonstrate how the new fiber composite material analysis of VGStudio MAX can be applied to analyze typical woven fabrics to gather information about the layer structure and the orientation distributions within these layers.

2.1 Calculating 3D space orientations

The first step in analyzing the CT-data is to asses the general distributions of the fibers and their orientations. We thus first calculate the local 3D orientation for every voxel in a certain
user defined region of interest, as well as the mean orientation tensor and the fiber volume fraction for the whole region. To perform this analysis it is not necessary to be able to separate the individual fibers. Instead the developed software analysis tool can handle whole fiber bundles in the same way as single fibers by analyzing the local gray value gradient.

Figure 1: Slice views of the analyzed data set. The left image shows a slice in the orientation of the layers, on the right a cut through the sample visualizes the layer structure.

Figure 1 displays the analyzed dataset of a woven fiber structure. As a result of the orientation analysis the software then displays the histogram of the 3D space orientations (see Figure 2) either as equatorial plot or as a spherical plot with topography. From these histograms it is very easy to get an overview of the orientations in the whole analyzed region. Looking at the histograms of the analyzed dataset in figure 2, it is evident that the main orientations in this example are distributed in the x-y-plane, and that within this plane there are 3 dominant directions: along the x-axis (about zero degrees within the x-y plane) and two diagonal directions, roughly orthogonal to each other (about 45 and 135 degrees within the x-y-plane).

The local orientations can also be visualized both in 2D and 3D as vectors (see figure 3) or as color overlay. Additionally, the user may probe the calculated 3D orientation at any position of the analyzed region. Table 1 shows the mean orientation tensor calculated for the example dataset.

<table>
<thead>
<tr>
<th>xx</th>
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<th>zx</th>
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<td>0.0586</td>
<td>-0.0064</td>
<td>-0.0064</td>
<td>0.2832</td>
</tr>
</tbody>
</table>

Table 1: Statistical output of 3D space orientation analysis: the mean orientation tensor.

If there is one main or reference direction one can easily visualize the orientation deviations by specifying this direction directly in the spherical histogram (see figure 4). The angle deviations are then immediately displayed as a color overlay as seen in figure 5, where the different orientations in the neighbouring layers becomes obvious.
Figure 3: Visualization of 3D space orientation at different layer positions.

Figure 4: Specifying a reference angle directly on the spherical histogram. Orange colored sphere indicates default orientation.
2.2 Calculating projected angle to analyze orientations within the layers

The next step in the analysis will then be to calculate the orientations within the layers. To do so we define a plane orientation into which we project the local 3D orientations. Figure 6 shows a histogram of the projected angles. From this histogram one can easily see the 3 dominant directions within the layers. Analyzing the peaks in this histogram one can verify whether the angles of the fibers concur with the expected orientations.

The projected angles are also visualized again as color overlay (see right image in figure 7). A further result of the analysis is a plot of the individual components of the orientation tensor as displayed in figure 7 on the left. The black line plots the fiber volume fraction. The minimums in this periodic function indicate the borders between the individual layers. The red and green lines plot the xx and xy components of the orientation tensor respectively. They are shifted with respect to the fiber volume fraction line and show the orientations within the layers. It now becomes apparent that in this dataset there is always one layer where the main orientation of the fibers are oriented along the x-axis, followed by two layers with fibers distributed in the diagonal x-y-directions.
Figure 7: Left image shows part of the projected angle function plot (black line: fiber volume fraction, red line: orientation tensor xx, green line: orientation tensor xy). Right image shows visualized projected angle as color overlay in a slice image.

Figures 8, 9, and 10 show the orientations at different layer positions with maximum xx component (a layer with fibers almost only oriented in the direction of the x-axis), maximum

Figure 8: Projected angle: a layer with maximal xx. Left: analysis color overlay, middle: original gray-value image, right: histogram position

Figure 9: Projected angle: a layer with maximal xy. Left: analysis color overlay, middle: original gray-value image, right: histogram position

Figure 10: Projected angle: a layer with minimal xy. Left: analysis color overlay, middle: original gray-value image, right: histogram position
4. Conclusions

In this paper, we demonstrated on a real-world example how to analyze the orientations of woven fabrics using CT-data and the software VGStudio MAX. The tools can readily be applied to CT-data even if the resolution is not sufficient to separate every single fiber. Orientation distributions with multiple principal axes can easily be analyzed and the results of actual parts used directly for simulations. The analysis of CT scan data of fiber structures leads to an essential contribution to the quality control on the one hand and to the feasibility of important simulations on the other.

2.2 Calculate unidirectional deviations using reference orientation mode

For parts or regions of parts which contain a unidirectional distribution of the fibers, it is also possible to calculate the 3D deviations from a reference orientation.

3. Application to simulations

The possibility to use CT scan data to extract information of the fibers in woven fabrics creates an excellent data basis for more precise simulations of the mechanical properties of fiber composites and serves as reference for a simulation of the manufacturing process itself. Using the analysis results on the fiber orientations of VGStudio MAX it is easy to compare the actual orientations with the expected orientations for more precise simulations. Since the grid cells of the simulation software are typically much larger than the detailed level of information from the CT scan, it is therefore possible to define a grid or to directly import the fiber volume fraction information within these grid cells. This allows to use the actual orientations at each grid cell visualized as ellipsoids on some slice images aligned with the rowings at different layer positions and with a perspective rendering in 3D.

In a recent study by BASF, our software VGStudio MAX was verified using synthetic data as an accurate tool for computing fiber orientation tensors in CT samples. The analysis of CT scan data of fiber structures leads to an essential contribution to the quality control on the one hand and to the feasibility of important simulations on the other.

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hand without destroying the part. This is especially useful for further developments in the aerospace industry where lightweight design and safety concerns are crucial.

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References